The impact of population fluctuations on the spatial spread of Neolithic ceramic traditions in West Anatolia and South-East Europe

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Abstract

This article explores the relationship between population fluctuations and the development of similarity patterns in Neolithic ceramic assemblages from West Anatolia and south-eastern Europe. Its aim is to contribute to discussions surrounding the factors influencing material culture variation in prehistory. It compares population growth and decline rates reflected by the summed probability of radiocarbon dates to diachronic changes in the 'Isolation-by-Distance' (IBD) of ceramic assemblage similarities. The results indicate that there is a positive correlation between long-term population fluctuations and IBD, measured as the correlation between inter-site spatial distance and Jaccard dissimilarity of ceramic assemblages. This suggests that population levels affected the spatial extent at which information regarding ceramic production and style was transmitted.

These results are analyzed through discussing the influence of population size and density on cultural drift and on the spatial scales of cultural transmission. Population expansion is considered to have affected the spatial scales at which information as shared through networks and migration, while, population decline after 5900 BCE accelerated drift within regions as well as reducing the frequency of long-distance transmission, causing regional variation in ceramic traditions.

1. **Introduction**

Ceramics have been central to studying relationships between Neolithic sites in Anatolia and south-eastern Europe since the beginning of the 20th century (e.g. Wace and Thompson 1912, 240-9, Childe 1937, Gaul 1940, Milojčić 1949, Theocharis 1958, Todorova 1986, Nikolov 2004, Özdoğan 2011, Özdoğan 2015, Çilingiroğlu 2010, 2016). Many initial studies were strongly influenced by the cultural-historical approach (*sensu* Childe 1929), leading to a lasting view of Neolithic pottery traditions as compartmentalized along spatial boundaries. Both the spatial outline of Neolithic ceramic assemblage similarities and the analytical value of defining Neolithic culture zones in this area have been critically reassessed in recent years, leading to a replacement of theories of cultural diffusion by a focus on cultural transmission and learning (e.g. Amicone et al. 2019). However, our understanding of the long-term effects of cultural transmission processes is still often limited by the narrow time-scales employed in many studies. This article aims to improve our understanding of the driving forces underpinning variation between Neolithic ceramic assemblages from West Anatolia, Greece and the Balkans through addressing the impact of long-term population fluctuations and spatial distance. In doing so, it will contribute to a discussion regarding the social and demographic processes underpinning the spread of Neolithic pottery traditions in this area.

Population fluctuations are considered as a driving force behind long-term cultural change and variation (e.g. Hodder 1979, David and Lourandos 1988, Neiman 1995, Shennan 2000, Premo and Kuhn 2010). In the context of the rise of New Archaeology in the 1960's and 1970's, population growth was considered to lead to changes in material culture by provoking an adaptive response to the increasing pressure on available resources (Chamberlain 2006, 5). In contrast to views that understand material culture change from an exclusively adaptive perspective, observations from ceramic ethnoarchaeological research have highlighted the importance of social values and complex interaction systems, demonstrating that such factors influence the differential uses of material culture styles and technologies (e.g. Stark et al. 2008). This focus on social learning also underpins neo-Darwinian frameworks, which have shown that, next to the variable characteristics of transmission processes, stochastic processes involved in the intergenerational transmission of information contribute to the spatio-temporal spread of cultural traits (Cavalli-Sforza and Feldman 1982, Boyd and Richerson 1985, Shennan et al. 2015). Through providing a set of theories and quantitative methods, this framework allows for the empirical analysis of the conditions affecting long-term culture change and variation, including population size.

This article will explore long-term fluctuations in the spatial spread of Neolithic pottery assemblages in western Anatolia and south-eastern Europe, focusing on the period between 6600-5500 BCE. It will address the influence of population size on the stochastic transmission processes summarized as cultural drift. It will explore the extent to which long-term population fluctuations influenced the transmission of ceramic attributes by comparing proxies for population size and the spatial scales across which ceramic attributes were transmitted. Population fluctuations are modelled through the use of summed probability distributions (SPDs). Similarity patterns are analyzed through the Isolation-by-Distance (IBD) of ceramic assemblages, allowing for a long-term perspective on the 'regionalization' of cultural transmission.

1.1 Methods for estimating population fluctuations

Summed probability distributions (SPDs) can be used to explore past population fluctuations, using the premise that the more people lived in a given area, the higher the number of datable deposits are left behind (Rick 1987). In scholarship of the European Neolithic, they have been used as a proxy for regional population growth and decline (Shennan and Edinborough 2007, Shennan et al. 2013, Timpson et al. 2014, Weiberg et al. 2019), to understand the correlation between climate change and Neolithic settlement patterns (Weninger et al. 2009, Flohr et al. 2015), and to refine our understanding of regional discontinuities in the timing of the spread of farming from Anatolia to the Balkans (Brami and Zanotti 2015). SPD curves of the European Neolithic reveal population fluctuations that are often characterized by a signature of regional population growth from the beginning of the introduction of farming onwards, followed by a sudden decline ('bust') (Shennan and Edinborough 2007, Shennan 2012, Shennan et al. 2013, Timpson *et al.* 2014, Bevan et al. 2017). A similar boom and bust pattern has also been observed in the SPD curves of the Aegean and Central Anatolia and appears to broadly correspond to fluctuations in settlement patterning and environmental proxies (Weiberg et al. 2019; Woodbridge et al. 2019).

Despite these varied uses of SPDs, their significance for recognizing demographic signals remains contentious. One common critique of the using SPDs as a proxy for population fluctuations is that regional variation in the intensity of archaeological research as well as taphonomic processes might have resulted in an unequal spatio-temporal cover of radiocarbon dates, producing artificial peaks or troughs in the SPD curve (e.g. Attenbrow and Hiscock 2015). In order to account for potential biases relating to sites with disproportionate numbers of dates, recent studies have used a binning process, in which radiocarbon dates from the same site and from a similar age are grouped together before they are summed (e.g. Bevan et al. 2017, E10528). Nevertheless, uncertainties with archaeological sampling still pose a limitation on the use of SPDs in the research area considered. For example, Porčić et al. (2016, 12) suggest that a dip in the SPD curve of radiocarbon dates from the Central Balkans midway through the Neolithic derives from the disproportionate efforts to date the earliest Neolithic phases in the Central Balkans and a relative lack of dated deposits from later phases.

Contreras and Meadows (2014) observe that demographic signals are indistinguishable from SPD fluctuations created by statistical noise, a problem that pertains mainly to narrow time-scales and small datasets (see Timpson et al. 2014). Furthermore, Weninger et al. (2015, 559) note that folds in the calibration curve, deriving from fluctuations in atmospheric ^{14}C, lead to a failure of normalization, causing artificial peaks in the summed probability distribution. Such fluctuations have led to a steep decline between 8200-8120 BP followed by an approximately 80 year long plateau. This problem can be accounted for by using non-normalized dates, which produce a more reliable, albeit less detailed, SPD curve (Weninger et al. 2015, Bevan et al. 2017, Palmisano et al. 2017).

A range of methods have developed over recent years to account for random fluctuations in the SPD curve. Monte Carlo simulations, for example, allow for testing the significance of the SPD curve (e.g. Shennan et al. 2013, Crema et al. 2016). Kernel Density Estimation (KDE) is a method that allows for estimating the distribution of data points which can be used as an alternative to SPDs (Bronk Ramsey 2017). In contrast to the SPD method, KDE allows for controlling the parameters relating to degree of smoothing and shape of the curve. Although this method might reduce artificial peaks and noise, it retains the problem of smoothing potentially meaningful signals and produced curves broadly overlap with general signals already picked up through SPD.

Although these methods provide alternatives for SPD, accounting for some of the methodological issues of this method, in this research, it was decided to stick with regular SPD methods. In the first place this is because this research aims to provide a general estimate of meta-population levels from across southeastern Europe and West Anatolia over the period between 7000-5000 BCE. Through studying population fluctuations on an interregional scale and summing non-normalized dates, artificial wiggles and regional hiatuses in regional datasets are smoothed, reducing some of the taphonomy/research related biases that exist in sub-regions. Secondly, this research uses a method to quantify the relationship between population level and IBD, requiring a single average date from overlapping periods of 200-years, adding an extra level of smoothing that accounts for spurious peaks and high-frequency noise in the dataset.

The focus on meta-population fluctuations rather than regional fluctuations results in an interpretative challenge. For example, dips in regional population levels have been considered to spark periods of rapid culture change (Shennan 2000). Such details are lost both through combining regional datasets and through the level of smoothing employed in this study. As it remains a challenge to distinguish detailed demographic signals using any of the currently available proxies the analysis of the correlation between culture change and population size in prehistory is limited. The present study, therefore, mainly focuses on the relationship between population size and the spatial scales of cultural transmission rather than its effects on regional processes of culture change alone.

1.2 Regionalization and population fluctuations

There are several ways in which population growth might affect the regional transmission of cultural traits. Firstly, population growth is likely to increase the scale of community fissioning, resulting in an increase in settlement numbers. New settlements are likely to reproduce at least some of their pre-existing ceramic repertoire, causing similarities in the archaeological record. Secondly, increases in regional population densities might cause a growing number of groups to participate in interaction networks and the spatial distance between these interacting groups might decline as the density of settlement increases. David and Lourandos (1988) suggest that, in northern Australia, the increase in the density of networks following from population growth may have sparked the use of rock art styles as a marker of territoriality (e.g. 1988). In this case, therefore, population growth might have led to regionalization. However, as will be discussed below, regionalization may also result from population decline.

A key process that is considered to influence culture change and similarity is drift, which is strongly affected by population size. The speed at which cultural variants disappear through drift is low in large effective communities (i.e. active potters within a community), because there will be a large pool of students to adopt and transmit existing skills and ideas (Neiman 1995, 10). The high number of active members of a potting community ensures that skills and information are passed on to future generations, maintaining traditional knowledge and allowing for expansion of the variability within the community's material repertoires.

In small communities, random events (e.g. the deaths of a teacher, inadequate copying of knowledge, unconscious errors or deliberate inventions) have a much stronger effect on the transmission of information. For example, Premo and Kuhn (2010) have shown that the rate of local extinctions within a meta-population negatively influences the 'diversity, group differentiation and rates of long-term cumulative change' [2010, 5]. This relates to the expectation that drift destroys variation more quickly in small groups (Neiman 1995). Shennan (2000), on the other hand, points out that the expansion events following population decline might spark periods of rapid culture change. Due to a process that is equated to the biological process of 'peripatric speciation', new conditions encountered by expanding communities lead to innovative behaviour, which are further stimulated by the absence of social sanctions that would have been imposed within the parent population and fission relating to local populations growth (Rosenberg 1994, Shennan 2000, 815).

Although both examples explore the effects of population fluctuations on cultural diversity, it is less clear what happens during a period of long-term population decline, such as we can expect during the final stages of the Neolithic in Europe. As Premo and Kuhn (2010) have shown, drift destroys the variability within assemblages, which, in the event of a high local extinction rate within a meta-population results in the long-term uniformity and similarity of material assemblages. However, if assemblages are highly diverse as well as highly similar to begin with, perhaps we can expect a different outcome. If a meta-population declines, local groups might lose some pre-existing knowledge due to the effects of drift. If transmission is neutral (i.e. if there are no selective advantages or other biases causing the transmission of certain traits over others) population decline might lead to a random loss of cultural variants used in each region, causing differentiation rather than uniformity between regions. A key aspect of understanding the relationship between population fluctuations and regionalization in cultural assemblages is therefore to study changes in the spatial scale of similarities.

As discussed above, the expansion of transmission lineages through fissioning might lead to the spread of similar ceramic assemblages. However, similarities can also derive from horizontal transmission, through the exchange of information between peers deriving from interacting communities. The interaction networks underpinning horizontal transmission are, therefore, important mechanisms for the distribution of cultural variants. A further consideration in this respect is that the transmission of cultural information is usually regulated or 'biased' in some way. Biased transmission (i.e. conformity-, anti-conformity-, prestige-, content bias) describes the intentional selection, discovery or invention of cultural traits by individuals or social groups. Biased transmission counter-acts the effects of drift, delaying the speed at which traits disappear or actively stimulating the uptake of new attributes (e.g. Eerkens and Lipo 2005, 323-326). Biased forms of transmission might also shape the spatial outline of transmission networks, leading, for example, to the polarization of the ceramic traditions of neighbouring groups (e.g. Roux et al. 2017).

Although sharp boundaries between potting groups might derive from context specific social learning systems (e.g. Gosselain 1994, 2000, Wallaert-Pêtre 2001, Dietler and Herbich 1989), several studies have shown that, in general, cultural similarity tends to decrease as spatial distance increases (Collard et al. 2006, Rogers and Ehrlich 2008, Ross et al. 2013, Shennan et al. 2015). This phenomenon, referred to as 'Isolation-by-Distance' (IBD), indicates the degree to which spatial distance limits the frequency of intergroup cultural transmission. The correlation between spatial distance and ceramic assemblage similarity are, in this study, taken as a measure of IBD. Fluctuations in the strength of this correlation might signal the emergence or disappearance of specific contact patterns. These might be affected by population size. For example, if cultural transmission is neutral and population levels are high, we can expect the development of a strong correlation between IBD and spatial distance. Because drift destroys diversity in small populations, population decline should lead to homogeneity in the long run (e.g. Neiman 1995, 14). However, as population decline might also increase the isolation between communities there is no easy answer as to how it affects IBD patterns. By comparing IBD to the population fluctuations suggested by SPDs, the following will explore the nature of processes of regionalization in Neolithic ceramic assemblages.

2. **Materials and methods**

2.1 The dataset

This research employs statistical methods to identify similarities between Neolithic ceramic assemblages, based on variation in the numbers of shared ceramic attributes. It focuses on those attributes that represent the visual style (attributes considered to be decorative and malleable such as shapes, surface treatments, types of handles, bases and rims, and ornamental decorations). Ceramic ethnoarchaeological studies have shown that such attributes tend to cross group boundaries more frequently than technological skills and ideas (e.g. Gosselain 1994). High similarities between ceramic assemblages based on such attributes can therefore be considered to indicate the *'the most important and frequently activated social relationships among settlements'* (Mills et al. 2013, 5765).

The present study uses a dataset of ceramic attributes relating to Neolithic ceramic assemblages from 56 site-phases from West Anatolia and south-eastern Europe, compiled during the author's PhD research (de Groot 2016). The temporal coverage spans the period between ca. 6600-5500 BCE, covering the Middle and Late Neolithic in West Anatolia, the Early and Middle Neolithic in Greece, and the Early Neolithic in Bulgaria, Macedonia and Serbia. Attribute-presences were collected from site-reports, monographs and articles, MA and PhD-theses and through collection and depot visits in Turkey, Serbia and Bulgaria and structured utilizing the assemblages' 'site-phases' as a spatial and temporal reference (Figure 1, Supplementary Table 2). The resulting binary dataset records the presence of 136 attributes relating to vessel shape, decoration, surface treatment and handle-, base- and rim types at each of the sampled site-phases.

2.2 The Jaccard Index and Mantel test

Pairwise similarities between these site-phases were calculated using the Jaccard Index. The Jaccard Index is a commonly used similarity measure in archaeological research because it calculates the overlap between pairs of observations whilst ignoring all the absent values (Hodson 1977, 1990, Crema et al. 2014, Shennan et al. 2015). As a result, missing data does not bias the overlap between compared rows, making it a popular method for studying similarity patterns in archaeological datasets, which are incomplete or fragmentary by nature. Because the Jaccard Index treats all observations as equal, it does not provide information about dominance relationships between sites or hierarchical structures in the attribute dataset (e.g. Habiba et al. 2018, 65). Furthermore, because it uses binary data, the Jaccard Index is influenced by variation in the diversity of present attributes, which might be strongly affected by archaeological sampling biases (e.g. Kintigh 1984, Chao et al. 2005). Despite these problems, these biases are expressed in the general similarity patterns as noise rather than resulting in false relationships (e.g. Habiba et al. 2018, 69). The Jaccard index is, therefore, a useful method for defining the general distance decay of attributes over space using a binary dataset, while more detailed information about pairwise similarities can be derived from comparing a range of similarity measures or using fully quantified datasets if available (Ibid. 2018).

In order to measure the IBD of ceramic assemblages, this research compares the relationship between Jaccard dissimilarity and pairwise spatial dissimilarity. This correlation can be measured using a Mantel test, which uses a permutation test to calculate the significance of the goodness-of-fit between two matrices (Mantel 1967, Cochrane and Lipo 2010, Crema et al. 2014). The Mantel test calculates a measure between 0 (no correlation) and 1 (perfect correlation). The results of the Mantel test are compared for groups of site-phases relating to distinct time-periods in the interval between c. 6600 – 5500 BCE (Supplementary File).

2.3 SPD

Radiocarbon dates and spatial coordinates were collected through systematic search and analysis of publications and online repositories (e.g. Reingruber and Thissen 2016, Gatsov and Boyadzhiev 2009, Weninger et al. 2009, Luca and Suciu 2011, Brami and Zanotti 2015). Because, many radiocarbon dates from mainland Greece have on average two to three times larger standard deviations than those from Anatolia, which were sampled and analyzed more recently (Brami and Heyd 2011, 173), this research has introduced an extra control by using only radiocarbon dates with standard deviations of less than 200 years (following Brami and Zanotti 2016). Using the R package ‘rcarbon 1.1.2’ (Bevan and Crema 2017) and the IntCal13 calibration curve (Reimer et al. 2013), dates were divided into 100-year bins to produce both a normalized and a non-normalized SPD (Figure 2, Supplementary Table 1). Figure 2 shows that population levels steadily increase from 9000 BP (7050 BCE) onwards. The non-normalized SPD suggests a steady rise in population density, probably based on both intrinsic growth and immigration, and a gradual decline after 5900 BCE. The normalized SPD curve demonstrates that there are three peaks within the interval (around 6450 BCE, around 6100 BCE and around 5700 BCE) and a gradual decline in summed probabilities after this last peak.

3. **Results**

In order to reveal fluctuations in the influence of pairwise spatial distance on ceramic assemblage similarity the site-phases were divided into ten overlapping 200-year time-intervals using a combination of absolute and relative chronological information (de Groot

2016, 81-133). The Mantel r^2 scores of each of the overlapping 200-year time-intervals (Supplementary Tables 6-7) provide an indication of the development of IBD through time. These scores were plotted against the background of the SPD of the period 8500–7500 BP (6550-5550 BCE) (Figure 3). The Mantel test results indicate that there is an increasing goodness-of-fit between spatial distance and ceramic assemblage similarity, which indicates that through time, the spatial distance between highly similar ceramic assemblages shortened. Network visualizations of these pairwise similarities demonstrate that strong interregional similarities persist during the Neolithic (de Groot 2019, 8, Figures 2-3). However, regional similarity networks appear in mainland Greece and the south-eastern Balkans respectively after 6000 BCE, indicating that the increasing Mantel scores are the result of more spatially regular similarity patterns in the later intervals of the temporal frame of this research.

As shown by Figures 3 and 4, this regionalization, which intensifies after 6000 BCE, is mainly visible in the decorative styles and surface treatments used across the research area. Ceramic shapes are not strongly positively correlated with spatial distance, suggesting that decorative and stylistic attributes are a more informative class of ceramic attributes to identify intergroup cultural transmission, whilst shapes are generally of little value to study transmission on the spatio-temporal scale employed in this study.

The average summed probabilities for each of the 200-year time-intervals were compared to the Mantel r^2 scores using the Spearman's rank correlation coefficient, which calculates a value of 0 when there is no correlation and 1 if there is a perfect correlation between two sets of observations. Spearman's rank correlation scores were calculated using the Mantel test results and the average summed probabilities over each of the corresponding 200-year time-intervals. The Spearman's rank correlation coefficient confirms that IBD in ceramic shapes is not correlated to the SPD curve. Instead, the fit between summed probability and the Mantel r^2 values relating to the IBD of decorative-stylistic attributes is positively correlated with both the normalized and non-normalized SPD curves. The sequence of Mantel scores relating to the IBD of all attributes combined produces an even higher Spearman's rank correlation r_s (Table 1), and fits best with the normalized SPD curve. This shows that the SPD curve is positively correlated with the long-term move towards regionalization in ceramic style-decoration, but that this is particularly strongly expressed when using the normalized SPD curve as a population model. The lower Spearman's rank correlation produced from comparing the Mantel test results to the non-normalized SPD curve relates to the dissonance between a steady increase in Mantel scores and a gradual drop in summed probability after c. 5900 BCE. This suggests that, whilst overall population levels might have started to decline in the later stages of the interval, regional differences in ceramic traditions continued to intensify.

Table 1. Spearman's rank correlation of the summed probability distributions of normalized and non-normalized calibrated ^{14}C dates from West Anatolia and south-eastern Europe, compared to a sequence of ten Mantel r^2 scores (relating to groups of site-phases in overlapping 200-year time-intervals) of the correlation between inter-site spatial distance and Jaccard dissimilarity. Summed probabilities of the normalized and non-normalized distributions were smoothed using a moving average filter with 200-year window.

	Decorative/stylistic attributes	*Shapes*	*All attributes combined*
Spearman's rank correlation r_s using non-normalized SPD ~ p-value	0.4424 ~ 0.2042	0.091 ~ 0.811	0.6 ~ 0.073
Spearman's rank correlation normalized SPD r_s ~ p-value	0.5879 ~ 0.08	-0.0303 ~ 0.946	0.6485 ~ 0.05

4. **Discussion**

The results indicate that the increasing influence of spatial distance on ceramic assemblage similarity is positively correlated with the increasing summed probability of radiocarbon dates. This suggests that regional intergroup cultural transmission occurred more frequently after 6000 BCE, following on a gradual increase in the summed probability of radiocarbon dates. The correlation between similarity and spatial distance intensified steadily through time, even though population levels appear to decline after 5900 BCE. How can we explain this increasing regionalization in the light of long-term population fluctuations during the Neolithic?

The introduction of ceramic technology in the Aegean and the Balkans broadly coincides with a major socio-economic transition marked by the spread of farming. Widespread 'pioneer' farming migration as well as the adoption of domesticates by resident Mesolithic groups in the Aegean (e.g. Horejs et al. 2015) and the rapid Neolithization of the Balkans (e.g. Biagi et al. 2005) will have affected the distribution of similar ceramic production traditions and visual styles. Examples of this are Early Neolithic ceramic traditions such as dark-faced burnished ware in Central and NW Anatolia and red-slipped burnished or ‘monochrome’ ware in the Aegean Region, which appear in early farming contexts in southern Anatolia and the Aegean Region respectively (Brami and Heyd 2011, 188). This widespread use of similar pottery, introduced alongside or slightly after the spread of farming technologies seems to be reflected by the low IBD values before 6000 BCE, indicating that geographic proximity does not explain similarity during this period.

However, although long-distance migrations/interactions are thought to have underpinned the widespread use of stylistically similar monochrome and dark-faced burnished wares, the homogeneity of early pottery traditions requires further thought. By a process described as ‘founder effects’, prehistoric migration processes can cause variation in material assemblages. The effects of drift are more prominent in small founder communities, leading to differentiation between isolated communities deriving from the same parent population. Furthermore, by a process equated to peripatric speciation, fission relating to expanding local populations combined with an adaptive response to the new environment might lead to a higher innovation rate, causing regional differences in material assemblages (e.g. Rosenberg 1994, Shennan 2000). Founder effects can be expected given that one of the predominant views explaining the Neolithization of south-eastern Europe is that farming spread through a leapfrog colonization process (e.g. Zvelebil 2001, 2, van Andel and Runnels 1995, Çilingiroglu and Çakirlar 2013). Leapfrog colonization is a process by which small groups of pioneer farmers settled in favorable locations (for example river valleys or floodplains), the resources of which would be used until local populations outgrew the environmental carrying capacity. Under the conditions of founder effects, the material assemblages in of pioneer farmers should have developed individual characteristics. However, instead of the onset of regional variation after the period of pioneer farming in Anatolia and the Aegean, which dates to at least 6600/6500 BCE, we find a continuation of low IBD signals until 6000 BCE. The maintenance of at least two sets of cultural attributes (e.g. monochrome and dark-faced burnished ware), which is replicated across the Aegean, suggests that strong measures were taken to ensure continuity of practices.

This possibility suggests that conformist transmission caused strong similarities between the earliest pottery assemblages. Perlès (2001), for example, suggests that persistent social restrictions on pottery making could have discouraged accidental or deliberate decorative or morphological innovations up until the end of the Early Neolithic, when more variable assemblages started to appear (e.g. Perlès 2001, 219). The homogeneity in the monochrome wares of the Greek Early Neolithic might have intensified through the exchange of potters by means of an intermarriage structure (e.g. Wijnen 1993, 324, as quoted by Perlès 2001, 219), although this latter possibility does not explain the interregional similarities observed.

Similarity in Early Neolithic ceramic traditions might relate to conformity in the transmission of cultural knowledge in pioneer farming communities. However, we also need to take into account the possibility that Early Neolithic ceramic assemblages were rarely decorated, with a low variability of shapes and wares (e.g. Özdoğan 2015). The relatively low decorative diversity also reduces the scope for identifying regional variation. Furthermore, some researchers suggest that the narrow scale of excavated Neolithic deposits limits our understanding of the true variability of attributes in early assemblages (e.g. Krauß 2011).

Nevertheless, in centuries that followed, IBD signatures remain low, even though the regional diversity of attributes notably increases (e.g. Perlès 2001, 219). This might relate to frequent horizontal intergroup transmission taking place after the spread of farming. Long-distance interaction networks are considered to persist in the Aegean throughout the Neolithic period as attested by the presence of obsidian from Melos across the region (e.g. Milić 2014), evidence for ongoing geneflow between South-East European and Anatolian cattle (Scheu et al. 2015) and the spread of impressed ware ceramics, signalling the widespread interactions of Neolithic communities in the Aegean around 6100 BCE (Çilingiroğlu 2016). Decorative variants such as red-on-white painted ware in the Aegean, white-on-red painted ware in the Balkans, and calcite-encrusted decorations in the Balkans and Aegean might further reflect the widespread networks of Neolithic communities in these areas. Geographical features such as the Aegean Sea will have affected the distances covered by population movement and interaction and therefore also the spatial extent of ceramic assemblage similarities during the Neolithic. Due to the continued exchange of pottery attributes along Aegean networks, low IBD signals might have persisted throughout the 7th millennium BCE. Long-distance networks, shaped by geography (the Aegean Sea, the location of obsidian sources) and social networks (based on personal or group relationships, ancestral ties, commercial motives, survival mechanisms, shared subsistence strategies, etc.) therefore might also explain the low IBD measures before 6000 BCE.

Next to the continued influence of Aegean networks in the transmission of ceramic attributes, a range of social factors may have created irregularities in the spatial drop-off of ceramic assemblage similarity. Transmission biases might have led micro-regional differences between pottery assemblages (Özdoğan 2013, Urem-Kotsou et al. 2014). Furthermore, a new phase of expansion of farming into the Balkans occurred around 6100 BCE. Neolithic sites suddenly appear across a vast region, potentially as a result of a rapid process of migration along the southern European river valleys (Biagi et al. 2005, Krauß et al. 2017). By this time, the decorative and morphological variability of ceramic assemblages is much higher than in the Aegean Early Neolithic. However, rather than producing new ceramic decorations and shapes idiosyncratically, the early farming groups that appeared in the Starčevo-Criş region and northern Bulgaria draw upon a similar repertoire of decorations, shapes and (temper) techniques, suggesting again that a level of conformity to using established traditional knowledge may have acted upon the reproduction of ceramics in pioneer settlements in the Balkans.

Elsewhere I have discussed the relationships between the ceramic assemblages studied here through analyzing them as diachronic network patterns (de Groot 2019, 8). This has shown that the distance between highly similar assemblages tends to decrease after 5900 BCE, suggesting that long-distance relationships might have been replaced by shorter distance similarities after this period. Considering the shape of the non-normalized SPD curve (Figure 3), the onset of the shorter-distance relationships around 5900 BCE corresponds to a period when summed probabilities of radiocarbon dates start to decrease. Reiterating here that the SPD curve represents population fluctuations across the entire research area, the timing of the onset of population decline in sub-regions such as Anatolia is masked (e.g. Brami and Zanotti 2015, 112, Figure 8). The asynchronous onset of regional population decline might well have led to a disappearance of the interregional exchange networks that facilitated cultural transmission. Although a better understanding of regional population curves is necessary to support this hypothesis, the improving Mantel test results after 6000 BCE could signal a shift from long-distance networks to close-distance interactions, caused by regional population decline.

In order to explain the regionalized transmission, it is important to consider both population fluctuations and contextual evidence. After the spread of farming to the Balkans, the spatial scales of fissioning and interactions might have narrowed, resulting in closer distance similarities. On the other hand, established long-distance networks may have been disturbed as a result of regional population decline. If populations in areas such as West Anatolia indeed declined, this may have affected the scale of the Aegean networks and therefore also the scale of information transmission. Declining regional populations are expected to be affected more strongly by drift, leading differentiation between communities and the more rapid disappearance of pre-existing knowledge (provided that transmission is neutral). Perhaps communities in each region formerly part of the same network will have separately reproduced a random selection of ceramic attributes from a previously shared set of attributes, reducing the similarity between distant ceramic assemblages.

These possibilities require further investigation. However, as the results of this research show, regionalized variation in the sorting of ceramic attributes is likely to be the result of processes occurring after the spread of farming to the Balkans, demonstrating that other processes than demic diffusion affected long-term patterning in Neolithic ceramic assemblages from the region considered.

5. **Conclusion**

This article has discussed a novel method to compare contemporary proxy datasets for population fluctuations and material culture patterning. The results obtained in the study support the hypothesis that fluctuations in the summed probability of calibrated radiocarbon dates and the increase in the influence of distance on ceramic assemblage similarity are related and, therefore, that population fluctuations should be considered as a factor in explaining the trajectory towards regional uses of ceramic attributes in Neolithic West Anatolia, Greece and the Balkans. As shown in the discussion, however, the relation between population fluctuations and the regional cultural transmission of information and skills regarding ceramic production is by no means straightforward, as there are specific contextual factors (e.g. transmission biases, geographic features and interaction networks) that might have contributed to the development of patterns in the similarity between Neolithic ceramic assemblages from Anatolia and south-eastern Europe.

Contextual information regarding the processes of interaction and migration part of the Neolithization of south-eastern Europe has shown that IBD signals across this region might be correlated to a process of population decline rather than early onset population growth and expansion. However, in order to investigate this hypothesis, it is key to further investigate the timing and nature of population decline processes. Although it has not been the primary aim of this article to compare methodologies for modelling past population growth and decline rates, a future study comparing different proxy datasets for population fluctuations in each of the sub-regions discussed can help identify the onset of population decline, aiding our understanding of the emergence and decline of interregional interaction networks.

A further line of research will be to discuss fluctuations in the spatial extent across which attributes were generally distributed. This can help identify the influence of population growth and decline on the general range across which attributes were transmitted. Doing this will require a higher resolution dataset of pottery attributes, and a focus on establishing the distance at which the IBD curves reach a plateau (see also Crema et al. 2014, Supplementary File).

Finally, binary data have been used in this article because it offers the lowest common denominator for comparing ceramic assemblages published at different levels of detail. The availability of quantitative frequency datasets would provide a more detailed reflection of interregional similarities in the research area. Conclusively, although the results of this study are preliminary, they demonstrate that new insights about the spread of pottery traditions in Neolithic West Anatolia and South-East Europe can be gained through taking into account population fluctuations.

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